

THE PLAN FOR TOMORROW

Compile-Time Extension Points for C++ Libraries and Applications



ThePhD - [@thephantomderp](https://twitter.com/thephantomderp) – [LinkedIn](https://www.linkedin.com/in/the-phd/) - <https://thephd.github.io>
Columbia University Student, May 10th, 2019
C++Now2019, Aspen, Colorado



EXTENSION GOALS: ADDING FUNCTIONALITY...

- beyond what was initially considered by application / library authors
 - Callback functions with `void*` userdata in C libraries
- to perform some semantically-expected task for types outside author's purview
 - `std::swap`
- to endow a class with a specific, compatible interface
 - virtual protected functions in iostreams

WELL-KNOWN EXTENSION METHODS

A brief overview of compile-time and runtime hybrid extension technology

WELL-KNOWN: VIRTUAL METHODS

- No surprises here: create base class and stuff it with virtual methods

```
struct animal {  
    virtual std::string sound () const = 0;  
};  
  
struct dog : public animal {  
    virtual std::string sound () const override {  
        return "woof";  
    }  
};
```

WELL-KNOWN: VIRTUAL METHODS USAGE

- Used extensively up to ~2008, less so now in place to static polymorphism
 - Many game engines: Ogre, Irrlicht, Doom, etc...
 - Qt: `QObject` and the entire class tree
 - Clang: `ASTMatchers` and extension points
 - C++ standard library: iostream customization points
 - One too many C++ university classes

BENEFITS

- Can work with super class (base class) at compile-time
 - calls the right method at runtime
 - no need to bookkeep function pointers and similar
- Heavily optimized by compiler writers to de-virtualize simple cases
 - E.g.: current-gen non-user-specialized iostreams, C++ XAML, and more

DRAWBACKS

- ABI-brittle
 - adding a function to class might append to virtual table, but may insert in middle of derived class's virtual table
 - difficult to detect mismatches
- Runtime efficiency
 - Does "X" *need* to be virtual? Must decision be delayed to runtime?
- Implementation-controlled Virtual Tables / Slicing Problem
 - Base classes must be handled as pointers / references or risk slicing

CALLBACKS WITH USERDATA

- Function which takes a strongly-typed function pointer and a void* userdata
 - Staple of C APIs everywhere, including some C standard library functions
 - Highly flexible
- Used to let (application) developer do things beyond what was envisioned
 - e.g., serialize data into to a std::vector instead of a FILE*

```
typedef int (*lua_Writer)(lua_State*, const void*, size_t, void*);  
  
int lua_dump(lua_State* L, lua_Writer writer, void* userdata, int strip_symbols);
```


WELL-KNOWN: CALLBACKS WITH USERDATA USAGE

- Literally every C library, ever...
 - Lua, libclang,
 - libpng, libjpeg
 - jansson, libev, freetype
 - Win32: everywhere
 - C Standard Library: qsort

EASY TO WRAP IN C++

- Typical C call, wrapped in C++

```
template <typename Callback>
int dump_handler(lua_State* L, const void* data, size_t data_size, void* userdata) {
    Callback& callback = *static_cast<Callback*>(userdata);
    return callback(L, data, data_size);
}
```

```
template <typename Callback>
void dump_with(lua_State* L, Callback&& callback, bool strip_symbols = true) {
    lua_Writer writer = &dump_handler<std::remove_reference_t<Callback>>>;
    void* userdata = static_cast<void*>(std::addressof(callback));
    lua_dump(L, writer, userdata, static_cast<int>(strip_symbols));
}
```

EASY TO WRAP IN C++: NO TEMPLATES

- Fix the interface to save on template duplication for every callable...

```
using dump_function = std::function<lua_State*, const void*, size_t>;

int dump_handler(lua_State* L, const void* data, size_t data_size, void* userdata) {
    dump_function& callback = *static_cast<dump_function*>(userdata);
    return callback(L, data, data_size);
}

void dump_with(lua_State* L, dump_function callback, bool strip_symbols = true) {
    lua_Writer writer = &dump_handler;
    void* userdata = static_cast<void*>(std::addressof(callback));
    lua_dump(L, writer, userdata, strip_symbols);
}
```

EASY TO WRAP IN C++: NO TEMPLATES

- `std::function` is expensive
 - Higher efficiency, low cost for (maybe) C++20: `std::function_ref`

```
using dump_function = std::function_ref<lua_State*, const void*, size_t>;
```

```
int dump_handler(lua_State* L, const void* data, size_t data_size, void* userdata) {  
    dump_function& callback = *static_cast<dump_function*>(userdata);  
    return callback(L, data, data_size);  
}
```

```
void dump_with(lua_State* L, dump_function callback, bool strip_symbols = true) {  
    lua_Writer writer = &dump_handler;  
    void* userdata = static_cast<void*>(std::addressof(callback));  
    lua_dump(L, writer, userdata, strip_symbols);  
}
```

EASY....?

- Inline and synchronous execution:
 - No need for storage
 - No need to manage lifetime
- Non-inline execution:
 - Calling it later (events in Qt, libev, etc.)? Need storage.
 - Multithreading? Need storage.
 - Storage means lifetime...

BENEFITS

- Space and time efficient
 - especially if callback never needs to be stored
 - function pointers are cheap
- ABI-hardy
 - difficult to break ABI unless the actual callback interface changes
 - user can place extra data into void* for their needs at no cost to library

DRAWBACKS

- Exception/early exit issues
 - if stored, is the callback called when an exception is tossed/failure is reported?
- In-lining optimizations for compiled code becomes restricted
 - `qsort(...)` vs. `std::sort(...)`
 - link time optimizations helps here
- Lifetime issues, when
 - storing the callback to call “at a later date”
 - multithreading concerns

COMPILE-TIME EXTENSION

Picking and choosing work to execute using compile time choices

EXTENSION METHODOLOGIES



- Compiler-Assisted
 - (Partial) Class Template Specializations
 - “Koenig”/Argument-Dependent Lookup (ADL)
 - Static friend functions
 - Template functions + Overloading
- Author Mandated
 - Traits/Policy/Agent templates

CLASS TEMPLATES + SPECIALIZATION

- Uses a class template
- User then (partially) specializes a class for this template
- Case studies: `sol2`, `std::hash`
 - Base template, user specialized templates
 - Using this class:

```
struct two_things {  
    int a;  
    bool b;  
};
```

SOL₂ AND STD::HASH

case studies in class template specializations

SOL::STACK::GETTER<T, C>

```
// sol.hpp, sol2
namespace sol { namespace stack {

    template <typename T, typename C = void>
    struct getter {
        static T get(lua_State*, int, record&) {
            /* default implementation here */
        }
    };

}} // namespace sol::stack
```

FULL SPECIALIZATION

```
// user.cpp
namespace sol { namespace stack {

    template <>
    struct getter<two_things> {
        static two_things get(lua_State*, int, record&) {
            /* user code here */
        }
    };

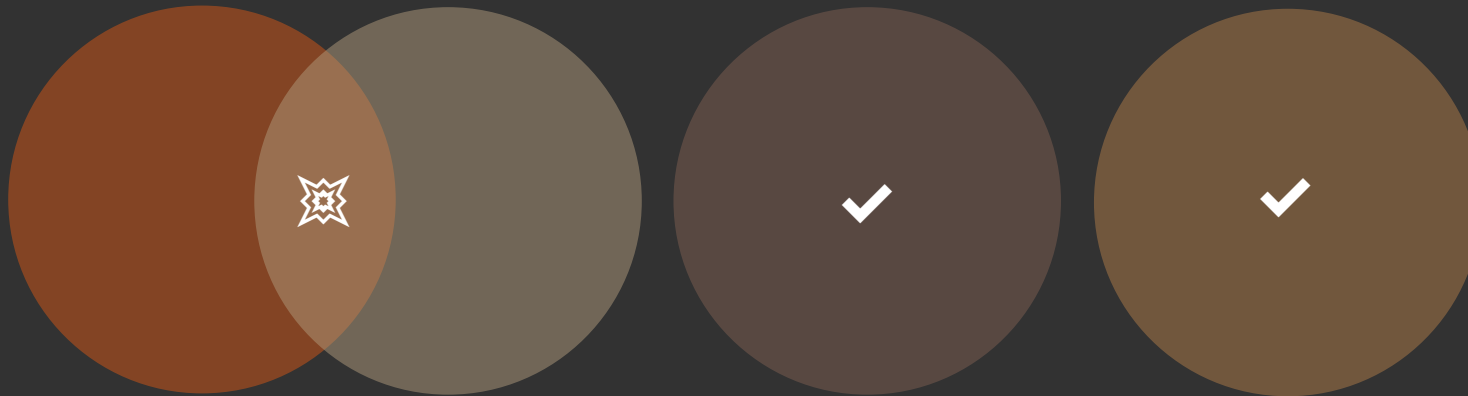
}} // namespace sol::stack
```

PARTIAL SPECIALIZATION

```
namespace sol { namespace stack {  
  
    template <typename T>  
    struct getter<T, std::enable_if_t<std::is_arithmetic_v<T>>> {  
        static T get(lua_State*, int, record&) {  
            /* implementation for all numerics */  
        }  
    };  
  
} // namespace sol::stack
```

DRAWBACK: MUTUAL EXCLUSION

- Fail to separate base implementation versus user implementation
 - All user customization points must occupy the same finite code space
 - All full and partial specializations must not collide (mutual exclusion principle)



- Bad design in sol2 led to a few annoying collisions/fighting with user specializations

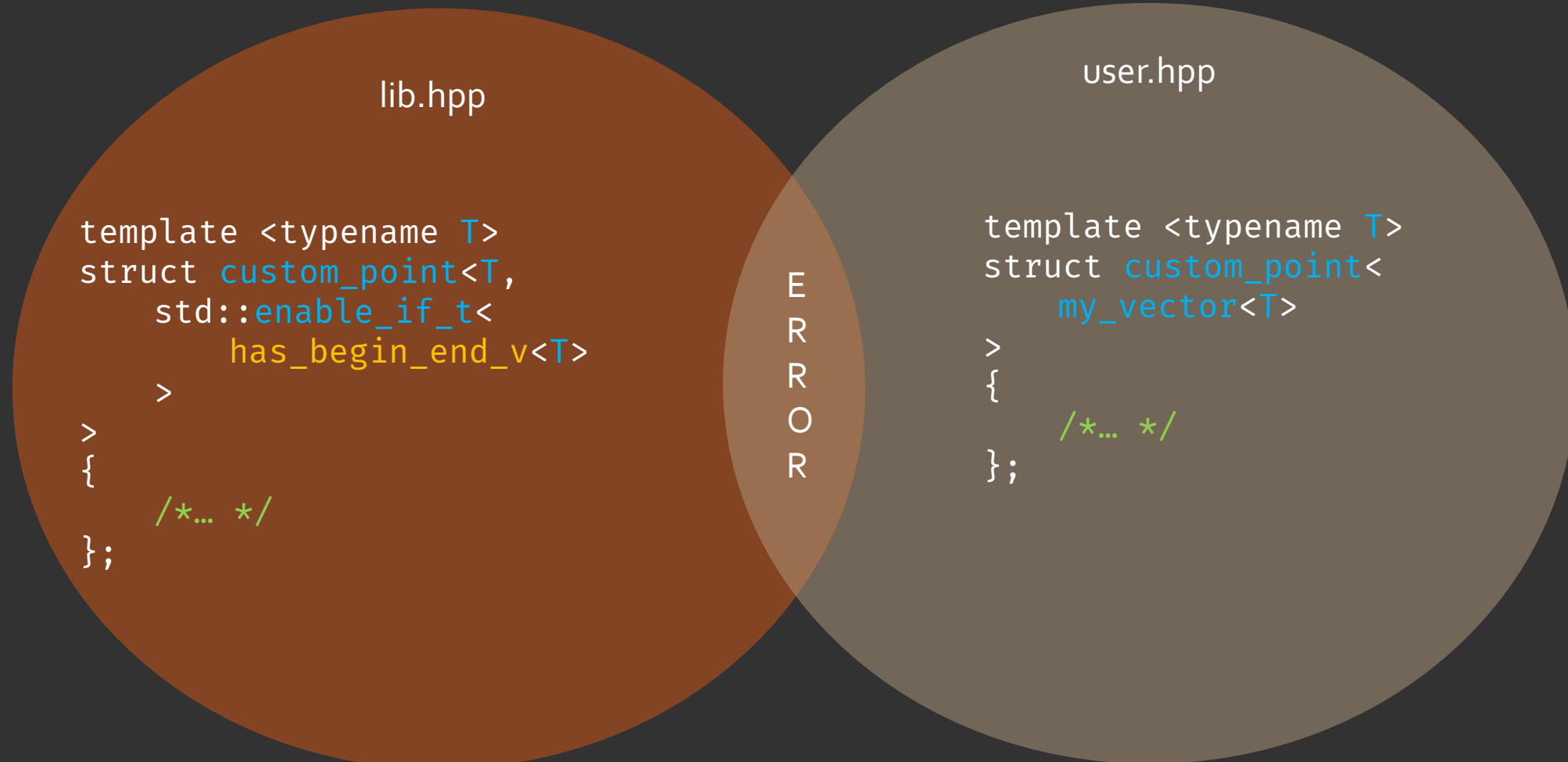
DRAWBACK: SPECIALIZATION COLLISIONS

```
namespace sol { namespace stack {  
    template <typename T>  
    struct getter<T, std::enable_if_t<std::is_integral_v<T>>> {  
        // ^ ERROR: ambiguous specialization  
        static T get(lua_State*, int, record&) {  
            /* implementation for integers */  
        }  
    };  
} // namespace sol::stack
```



DRAWBACK: SPECIALIZATION COLLISIONS

```
namespace sol { namespace stack {  
    template <>  
    struct getter<std::string> {  
        // ^ ERROR: multiple matches (sol2 has one already)  
        static std::string get(lua_State*, int, record&) {  
            /* implementation for std::string */  
        }  
    };  
} // namespace sol::stack
```

DRAWBACK: SPECIALIZATION COLLISIONS



DRAWBACK: VISIBILITY AND DEFAULTS

- Is the class template specialization...
 - visible in all possible translation units where it may be used?
 - body dependent on macros that are not defined for the entire build (and its dependencies?)
- Silent ODR violation that compiles, links and runs on all known compilers.
 - Problematic with all compile-time extension points where default is not a noisy error
 -  Specialization must be tightly packaged with class when used!
 - <https://thephd.github.io/oh-dear-odr-trap>

VISIBILITY AND DEFAULTS FIX?

- Undefined base template instantiation
 - Errors users when nothing matches with (cryptic) “there is no defined class here”
 - Impossible when you have a default implementation!

```
template <typename T>  
struct my_customization_point; // undefined base
```

FIX: SLIGHTLY BETTER

- Define base template, but static assert to give better error than compiler
 - Still impossible when you have a default implementation!

```
template <typename T>
struct my_customization_point {

    static_assert(always_false<T>::value,
        "no customization point was picked up; "
        "please define one or check your code!");

};
```

DRAWBACK: EXTRA TEMPLATE ARGS

- Extra template argument is needed on every extension point for SFINAE traits to be applied

```
template <typename T>
struct custom_point<T, /* SFINAE here */> {
    /* ... */
};
```

- SFINAE is messy
 - decltype() and `is_detected` SFINAE slightly less ugly than `std::enable_if_t`
 - introduces mutual exclusion principle problems

QUICK C++20 FIX: CONCEPTS

- Concepts allow for simpler partial specialization and remove SFINAE parameter

```
template <ContainerLike T> // concept-constrained
struct custom_point<T> {
    /* ... */
};
```

DRAWBACK: “ARCANE” KNOWLEDGE

- “The code isn’t working”
 - navigating the syntax and rules of template instantiations means glazed over looks and general confusion
 - when providing support, usually teach user about partial template specialization (or just give them an example)
- Typical C++ users just want to write simple code
 - Classes (with or without static functions): ✓
 - Functions (exported, inline, etc.): ✓
 - Templates (rules of ODR, visibility of specialization at time of use, etc.): ✗

DRAWBACK: HEADER BLOAT

- Header contamination becomes a real problem to avoid ODR issues
 - entirety of sol2 comes along for the ride
- produces longer build times
 - avoided with careful forward declaration of every required template and class
 - unfortunately, the standard itself does not provide forward-declaring headers
 - “modules will solve it?” – unfortunately, little tangible evidence I can personally provide

STD::HASH<T>

- Employs same struct specialization technique, but
 - is substantially simpler
 - has only one template argument
- Well-used, so this simple case has become idiomatic
 - lack of pre-C++20 SFINAE makes it easier to teach



STD::HASH<T> EXAMPLE

```
namespace std {  
  
    template<>  
    struct hash<two_things> {  
        size_t operator()(const two_things& tt) const noexcept {  
            auto h1(std::hash<int>{}(tt.a));  
            auto h2(std::hash<bool>{}(tt.b));  
            return my_hash_mix(h1, h2); // boost::hash_combine  
        }  
    };  
  
} // namespace std
```

BENEFITS AND DRAWBACKS

- Good: avoids arcane knowledge requirements by
 - being extraordinarily simple (write a function call operator)
 - not having a SFINAE parameter (avoids mutual exclusion)
- Bad: takes core specializations away from user
 - Pre-defined for `enum` types, integral types, etc.
 - No opt-out or overriding of those defaults
- Same visibility / header contamination issues
 - `<functional>` comes along for the ride 🐪, no forward declarations!


C++20 CONCEPTS: DRAWBACK?!



- Previously non-constrainable generic templates like `std::hash` are now... constrainable?!

```
namespace std {  
  
    template <Conceptified T>  
    struct hash<T> {  
        size_t operator()(const T&) const noexcept {  
            /* what have we done...? */  
        }  
    };  
  
} // namespace std
```

FREQUENT LIBRARY VENDOR COMPLAINT

- “They are opening up namespace std / my namespace !”
 - paper to solve this presented in Rapperswil, Switzerland, 2018; [p0665](#)
 - allows a user to specialize outside classes in the namespace where the class is defined
- Library vendors are hyper-sensitive to users opening up namespace std
 - people have done all sorts of interesting things in their code bases
 - required all large stdlib implementations to employ `__ugly_` `_Identifiers` for realies

(TEMPLATE) FUNCTIONS

Friendship and Overloading and ADL, oh my!


(TEMPLATE) FUNCTION OVERLOADING

- Step into the namespace of the function and add a similar name
 - does not depend on Name Lookup to “find” the function in associated namespaces
- Usually explicitly blessed by library author as “possible”
 - old usage: viable way to customize `std::swap`
- Case study
 - Boost.Serialization

ADDING OVERLOAD INTO BOOST.SERIALIZATION:

```
namespace boost { namespace serialization {  
  
    template <class Archive>  
    void serialize(Archive& ar, two_things& tt, unsigned int version) {  
        ar & tt.a;  
        ar & tt.b;  
    }  
  
}} // namespace boost::serialization
```

OVERLOADING: BENEFITS AND DRAWBACKS

- Direct additions to namespace separate extension point from target
 - benefit: if optional and not required, user can move customization function to independent header / implementation files
 - drawback: if required and not optional, then separation may not be desired and causes boilerplate/errors (“I forgot to include the special header for serialization”)
- Same complaint from library vendors
 - opening up other namespaces !
 - potential for name collisions and similar

INCREASING ENCAPSULATION: FRIEND

```
struct two_things {  
private:  
    friend class boost::serialization::access;  
  
    template <class Archive>  
    void serialize(Archive& ar, unsigned int version) {  
        ar & a;  
        ar & b;  
    }  
  
public:  
    int a;  
    bool b;  
};
```

FRIEND: BENEFITS AND DRAWBACKS

- Tight coupling!
 - benefit: if required, desirable to make it inseparable
 - drawback: compilation times for demanding Boost.serialization come along with the main header
- Makes library vendors happy
 - Titus Winters and the abseil team are smiling down at us (<https://abseil.io/tips/99>)

ARGUMENT-DEPENDENT LOOKUP

- Complicated set of rules
- Rely on namespaces of arguments to add additional symbols to unqualified calls
 - primary intentional use: “generic” (templated) code to work with arbitrary types
 - primary unintentional use: operators to “just find the right call” for `a == b`
- Case studies:
 - `std::swap` (the wrong way)
 - `std::ranges / range-v3` (the right way)

ARGUMENT-DEPENDENT LOOKUP: SWAP

- `swap(a, b)` // invokes ADL because call name is unqualified
 - looks in the namespace of `a` and `b`, as well as the current scope's namespace
 - likely a bug in generic algorithm if written outside `std`/a or `b` are not `std`
- `std::swap(a, b)` // does not invoke ADL because call name is qualified
 - looks only in namespace `std`
 - likely a bug if used in a generic algorithm

- Proper way:

```
using std::swap;  
swap(a, b);
```



“STD SWAP TWO-STEP”: VERBOSITY IS FAILURE

“The problem with the Two-Step is that it forces users to type *more* to do the right thing. FAIL. Most damning, it requires users to either blindly memorize and regurgitate the Two-Step pattern, or worse: understand two-phase name lookup in templates.”

– Eric Niebler, October 2014, <http://ericniebler.com/2014/10/21/customization-point-design-in-c11-and-beyond/>



ARGUMENT DEPENDENT LOOKUP: RANGE-V₃

- Create a callable function object which does the two-step with an internal detail namespace's swap
 - Invokes ADL but prevents qualified call to `ns::swap(a, b)` being a bug
 - ADL is done “for you”: function object takes care of it

ADL DONE RIGHT™

```
namespace std { namespace detail {  
    template <Swappable A, Swappable B> // important!  
    void swap (A& a, B& b) { /* default implementation */ }  
  
    struct swap_func {  
        template <Swappable A, Swappable B>  
        void operator()(A& a, B& b) const noexcept {  
            swap(a, b); // default swap already in scope  
        };  
    };  
}} // namespace std::detail
```

ADL DONE RIGHT™

- Create a constexpr object of the proper name sitting in the namespace

```
namespace std {  
    // C++17: inline variables clue compiler in to avoid ODR  
    inline constexpr const auto swap = detail::swap_func{};  
} // namespace std
```

ADL DONE RIGHT™ (C++14 AND BELOW)

- Create a constexpr object of the proper name sitting in the namespace
 - C++17: `inline constexpr` to avoid ODR issues, rather than `__static_const` trick

```
namespace std {  
  
    // older standards:  
    template <typename T>  
    struct __static_const { static constexpr T value{}; }  
  
    template <typename T>  
    constexpr __static_const<T>::value;  
  
    constexpr const auto& swap = __static_const<detail::swap_func>::value;  
  
} // namespace std
```

ADL DONE RIGHT™: VERY SIMPLE

```
struct two_things {  
    int a;  
    bool b;  
  
    // just this  
    friend void swap (two_things& left, two_things& right);  
};
```

WAIT, IS THAT A FRIEND FUNCTION?

- Friend functions contain a few encapsulation benefits and help avoid name collisions
- friend functions are the same as free functions, but:
 - hidden from qualified (`my_namespace :: func_name`) calls due to being inside the class
 - Findable (only) by calls which invoke ADL

FRIEND FUNCTIONS CASE STUDY: ABSEIL

- Abseil uses this extensively for its customization points
 - in particular, `AbslHashValue`

```
struct Circle {  
  
    template <typename H>  
    friend H AbslHashValue(H h, const Circle& c) {  
        return H::combine(std::move(h), c.center_, c.radius_);  
    }  
  
private:  
    std::pair<int, int> center_;  
    int radius_;  
};
```

BENEFITS: ADL DONE RIGHT™

- No Two-Step;
 - no subtle missed bugs in generic code
 - no inconsistency in “always qualify your calls”
 - Customization point writer gets there “first”
 - impose initial base-level concepts on the type
- Allows user to define swap in namespace next to class / as friend function
 - just a function: easy to write and read

DRAWBACK: OVERLOADING CATCH-ALLS

- Base implementation provided by author must SFINAE away or it will catch all calls and hard-error everything
 - must use `decltype` SFINAE, concept, trailing return type with `decltype` or `std::enable_if_t`
- Users may not properly constrain their overloads and write catch-alls
 - If users write a “generic” catch-all and do not properly constrain, the extension point is ruined for everyone

DRAWBACK: HIGH COLLISIONS

- Does your function take perfect forwarding references?
 - prepare to cry: overloads in the same space may consume more calls than intended
 - worse: they might even unintentionally work but do the non-performant / wrong thing!

```
namespace std {  
  
    template <class Pointer, class Smart, class... Args>  
        auto out_ptr(Smart& s, Args&&... args) noexcept;  
  
} // namespace std
```

DRAWBACK: HIGH COLLISIONS

- Basically working with a black hole
 - Avoid ADL for variadic forwarding functions: not a good time



```
namespace std {  
    template <class Pointer, class Smart, class... Args>  
    auto out_ptr(Smart& s, Args&&... args) noexcept;  
} // namespace std
```

MUST CONSTRAIN BASE IMPLEMENTATION!

```
namespace std { namespace detail {  
  
    template <typename A, typename B>  
    void swap (A& a, B& b) → decltype(a.swap(b)) { /* ... */ }  
  
    template <Swappable A, Swappable B>  
    void swap (A& a, B& b) { /* ... */ }  
  
    // and more...  
  
}} // namespace std::detail
```

BUT EVERYONE WILL PROPERLY CONSTRAIN!

And other lies I told myself after I read Eric's blog post...

NO.



- They will not constrain it.
- They will not use “only concrete types”.
- The world is not full of only experts.



ThePhD 02/02/2019

No idea why that trait is triggering and causing the error. I'll have to try to construct a small, reproducible error at some point, but my fix should get you going at least.
Oh.
That's why.
`tgui::to_string` is templated, and lying.
This has nothing to do with any of the classes or anything you wrote.



linbob 02/02/2019

i didnt think so



ThePhD 02/02/2019

`tgui::to_string` is a templated function that invokes `operator<<(YourClass&)` in order to serialize a string.
`sol2` picks that up when it goes through its complicated list of "does this thing have a `to_string` function".
`tgui` did not properly SFINAE-constrict its overload, so it says it takes `ContextMenu` when it, in fact, does not and the code inside cannot.
Templates were a mistake...
ADL was a mistake too.
Either way, nothing you or I can do about it. `tgui` would need to add some proper SFINAE to their templated function.
(Or just, you know. Not write a function like that.)

ADL DONE... RIGHT™?

- “The Best Anyone Could Have Done With The Tools At Hand.”
- range-v3 niebloids (begin, end, iter_move, dereference, etc.) contain no opt-out mechanism
 - does not prevent the ADL problem for unintentionally bad actors
 - makes it even more apparent when it does happen
 - cannot call “just the basic {begin/end/swap}” because it exists in an implementation-defined detail namespace now

ADL AND OVERLOADING: BIGGER PROBLEMS

- Functions can catch unintended calls
 - even if they are not templated
 - consider `void*` pointer conversions, derived \rightarrow base conversions, and more
- Results in a huge problems for ADL and overloading
 - unintended “catches” of base types and other things a user would find surprising
- Case study: sol3



ADL EXTENSION POINTS



- Associated extension points (not named the same!)
 - `sol::stack::get` a value maps to `sol_lua_get`
 - `sol::stack::check` a type maps to `sol_lua_check`
 - `sol::stack::push` maps to `sol_lua_push`

```
int sol_lua_push(sol::types<two_things>, lua_State* L,  
    const two_things& things);
```

```
two_things sol_lua_get(sol::types<two_things>, lua_State* L,  
    int index, sol::stack::record& tracking)
```

```
template <typename Handler>  
bool sol_lua_check(sol::types<two_things>, lua_State* L,  
    int index, Handler&& handler, sol::stack::record& tracking)
```


“DID YOU CUSTOMIZE THIS”: TYPE TRAIT IMPLEMENTATION

```
template <typename ... Args>
using adl_sol_lua_push_test_t = decltype(sol_lua_push(
    static_cast<lua_State*>(nullptr), std::declval<Args>() ...
));
```

```
template <typename ... Args>
inline constexpr bool is_adl_sol_lua_push_v =
    is_detected_v<adl_sol_lua_push_test_t, Args ... >;
```

SOL₃: ADL EXTENSION POINT FUNCTION CALL

```
template <typename T, typename... Args>
int push(lua_State* L, T&& t, Args&&... args) {
    if constexpr (is_adl_sol_lua_push_v<T, Args...>) {
        return sol_lua_push(...);
    }
    else {
        /* hit default if constexpr internals */
    }
}
```

SOL₃: AN EXAMPLE OF OLD PROBLEMS

- Why type tags?
 - To solve conversion problems; for example, pointer conversion rules

```
int sol_lua_push(lua_State* L, void* vp);
```

```
struct unrelated {};
```

```
int main (int, char*[]) {  
    sol::state lua{};  
    unrelated obj{};  
    unrelated* some_pointer = &obj;  
    // calls the above, not the default!  
    sol::stack::push(lua, some_pointer);  
    return 0;  
}
```

DRAWBACKS: ADL AND OVERLOADS

- Must guard against conversions
 - can develop smarter and more complicated traits
 - prefer a type tag if the space of the ADL is unconstrained
- Have templated functions that take multiple perfect-forwarding arguments?
 - just do not bother here; overload resolution will drive users crazy

TRAITS TYPES

Injecting compile-time extensions into the type system

TRAITS/POLICIES/AGENTS: TEMPLATED CLASSES



- Deployed for classes which need customizability
 - `std::basic_string<CharType, TraitsType>`
 - `std::basic_ostream<CharType, TraitsType>`
 - `std::vector<T, Allocator>`
 - `std::map<Key, Value, Predicate, Allocator>`
 - `glm::mat<Rows, Columns, Type, Precision>`
 - `nlohmann::basic_json<`
 `MapType, ArrayType, StringType, BoolType,`
 `SignedIntegerType, UnsignedIntegerType, FloatingType,`
 `Allocator, Serializer`
 `>;`

TRAITS: BAD REPUTATION

- Interfaces for `char_traits`, allocators, and more from the standard
 - early designs using new features in the standard
 - not thoroughly vetted
 - imbued in things it had no business being in (IO and friends)

Member functions

<code>assign</code> [static]	assigns a character (public static member function)
<code>eq</code> <code>lt</code> [static]	compares two characters (public static member function)
<code>move</code> [static]	moves one character sequence onto another (public static member function)
<code>copy</code> [static]	copies a character sequence (public static member function)
<code>compare</code> [static]	lexicographically compares two character sequences (public static member function)
<code>length</code> [static]	returns the length of a character sequence (public static member function)
<code>find</code> [static]	finds a character in a character sequence (public static member function)
<code>to_char_type</code> [static]	converts <code>int_type</code> to equivalent <code>char_type</code> (public static member function)
<code>to_int_type</code> [static]	converts <code>char_type</code> to equivalent <code>int_type</code> (public static member function)
<code>eq_int_type</code> [static]	compares two <code>int_type</code> values (public static member function)
<code>eof</code> [static]	returns an <code>eof</code> value (public static member function)
<code>not_eof</code> [static]	checks whether a character is <code>eof</code> value (public static member function)

TRAITS: LATER ITERATIONS SUCCESSFUL

- `std::map` and `std::unordered_map` made better use of traits
 - Predicate and Hash follow guidelines of `std::hash`
 - Single-responsibility principle for Predicate and Hash
- `nlohmann::json` is a templated type with sensible defaults
 - just change template parameter details if you do not like them!

NLOHMANN::JSON

- Does extensibility for its `to_json` / `from_json` calls by default as `adl_serializer`
 - Default serializer is actually really bad: default-constructs object, passes in ref to that object to fill in
 - But... nothing stops you from doing the following:

```
using json_but_with_good_serializer  
    = nlohmann::basic_json<..., good_serializer>;  
  
using json_but_with_optimized_map =  
    nlohmann::basic_json<spp::sparse_hash_map, ...>;
```

BENEFITS

- Easier to customize for user's needs
 - "I just need this one behavior in this localized area"
- Follows Chandler's C++ Principle
 - Pretty good performance by default, but then can flip the car hood up and start customizing things

DRAWBACKS

- Change the template, change the type
 - cannot interoperate with sibling types by default (unless explicitly programmed in)
- Brittle ABI
 - change default template parameters -> change name mangling
 - change template name -> any using/typedefs change name mangling
- “Too much customizability”
 - Need to resist temptation to repeat mistake of `std::char_traits`

SO... WHICH DO WE USE?

IT DEPENDS

- Each scenario has benefits and drawbacks
 - A bit of guidance for the scenarios

STRUCT SPECIALIZATION: BEST FOR PRECISE MATCHING



- Class SFINAE is some of the most expensive SFINAE one can perform
 - second only to non-concept function SFINAE in template arguments
 - SFINAE done on the return type of a function is faster
 - if constexpr is fastest
- Template matching is very precise and does not do even basic conversions
 - less flexible than overload conversions
 - must define template for base class, first derived, second derived, etc. even if they are all do the same thing
- Guidance: use for precise matching, internal details, no conversions

ADL: BETTER FOR STATELESS CONSISTENCY



- “pick up and play” feeling
 - works from anywhere, obeys the same rules (however complicated)
 - better for the library developer space
- sol3 picked ADL extension points for many reasons
 - user had to be able to be consistent across translation units
 - harder to have fixed ABI with trait-based state classes
 - `sol::state` / `sol::state_view` can work with underlying VM from anywhere
 - better for handling type-deficient Lua and C coding environment (interop)

ADL: STATELESS AND OLD CODE



- Guidance: use niebloids (range-v3) style...
 - when you know user does not need access to base implementation
 - when you are confident user will not do things to step on base implementation's toes
 - when you want to make sure someone can pass the functions to higher order functions
- Guidance: use sol3 separate-named-function style...
 - when getting to the default behavior in a well-defined way matters
 - when users are likely to define a large set of customizations
 - when users will be working with types they do not own often

TRAITS: BETTER FOR MULTITHREADED ENVIRONMENTS



- For when user has more control over the system and does not have to work in existing code
 - each class can have highly customized behavior specific to needs
 - avoids needing to share a single global universe of overload resolution / ADL space with others
 - great for application space
 - great for environments that are already type-rich / generic (C++)
- Can deploy one trait class in one area, another in a separate area
 - avoids ODR at the cost of having more types
 - highly-tailored needs

FUTURE TALKS?

- Fully Runtime Extension Points for C++ Applications
 - Unassisted Runtime DLL Loading
 - LoadLibrary + GetProcAddress / dlopen + dlsym
 - Hooking
 - mhook / LD_PRELOAD
 - Hot Reloading
 - Debug Gap Placements to compile new code into
 - Visual C++ debug compilation
- “Versioning” for the purposes of loading/calling code
 - ABI restrictions and friends

FUTURE TALKS?

- “The Future of Customization Points in C++23: Customization Point Functions”
 - Matt Calabrese’s p1292: <https://wg21.link/p1292>
 - He didn’t sign up to do this talk, but he is introducing a paper which makes customization points easy to write, read and reason about
- I think it would be a cool talk.
 - Hint hint.
 - Wink wink.
 - Nudge nudge.

FUTURE TALKS?

- “The Future of Customization Points in C++23: Customization Point Functions”
 - Matt Calabrese’s p1292: <https://wg21.link/p1292>
 - He didn’t sign up to do this talk, but he is introducing a paper which makes customization points easy to write, read and reason about
- I think it would be a cool talk.
 - Hint hint.
 - Wink wink.
 - Nudge nudge.
 - Hey Matt do the talk.

THANK YOU !



- Eric Feselier, Titus Winters
 - Challenged me to research generic extension mechanisms for `std::out_ptr` ([p1132](#))
- Isabella Muerte
 - “Tell them an ADL customization point is insane” (she was right; overloading concerns were insane)
- Lounge<C++>, include<C++>



QUESTIONS?



@thephantomderp

<https://twitter.com/thephantomderp>



The Pasture

<https://thephd.github.io>



Patreon - thephd

<https://www.patreon.com/thephd>



LinkedIn - thephd

<https://www.linkedin.com/in/thephd>

